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A peculiar H I cloud near the distant globular cluster Pal 4

Jacco Th. van Loon[1], Snežana Stanimirović[2], Mary Putman[3], Joshua E.G. Peek[4], Steven J. Gibson[5], Kevin A. Douglas[6], and Eric J. Korpela[7]
[1] *Astrophysics Group, Lennard-Jones Laboratories, Keele University, Staffordshire ST5 5BG, United Kingdom*
[2] *Department of Astronomy, University of Wisconsin, Madison, WI 53706, USA*
[3] *Department of Astronomy, Columbia University, New York, NY 10027, USA*
[4] *Department of Astronomy, UC Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA*
[5] *Department of Physics & Astronomy, Western Kentucky University, Bowling Green, KY 42101, USA*
[6] *Astrophysics Group, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom*
[7] *Space Sciences Laboratory, UC Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA*

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ABSTRACT

We present 21-cm observations of four Galactic globular clusters, as part of the on-going GALFA-H I Survey at Arecibo. We discovered a peculiar H I cloud in the vicinity of the distant (109 kpc) cluster Pal 4, and discuss its properties and likelihood of association with the cluster. We conclude that an association of the H I cloud and Pal 4 is possible, but that a chance coincidence between Pal 4 and a nearby compact high-velocity cloud cannot be ruled out altogether. New, more stringent upper limits were derived for the other three clusters: M 3, NGC 5466, and Pal 13. We briefly discuss the fate of globular cluster gas and the interaction of compact clouds with the Galactic Halo gas.

Key words: ISM: clouds — globular clusters: individual: Pal 4, M 3, NGC 5466, Pal 13 — Galaxy: halo — galaxies: dwarf — dark matter — radio lines: ISM

1 INTRODUCTION

The Galactic globular cluster system comprises about 150 clusters that are distributed throughout the Halo (Harris 1996). Though mostly concentrated towards the Galactic Bulge, five clusters (AM 1, Eridanus, NGC 2419, Pal 3, and Pal 4) are known at Galacto-centric distances around ~ 100 kpc — twice as far as the Magellanic Clouds! They are excellent probes of the gravitational potential of the Halo. They also probe the tenuous, hot ($\sim 10^6$ K) gas permeating the Galactic Halo (Spitzer 1956; Sembach et al. 2003; Bregman 2007), in particular through ram-pressure due to matter shed by the red giants in the clusters. These are evolved low-mass (~ 0.8 M$_\odot$) stars that will lose ~ 0.3 M$_\odot$ of material to the cluster's ISM before becoming ~ 0.5 M$_\odot$ white dwarfs (e.g., Rood 1973; Tayler & Wood 1975; van Loon, Boyer & McDonald 2008; McDonald et al. 2009). The main constituent of red giant winds is neutral hydrogen; with typical wind speeds ~ 10 km s^{-1} being slower than the escape velocity of a typical globular cluster (McDonald & van Loon 2007), there is a fair chance to find diffuse neutral hydrogen gas within globular clusters.

The globular cluster gas (GCG) has proven to be elusive, the only convincing detections being infrared emission from dust and 21-cm emission of atomic hydrogen in M 15 (Evans et al. 2003; Boyer et al. 2006; van Loon et al. 2006) and plasma in 47 Tuc deduced from pulsar timing experiments (Freire et al. 2001). The associations of H I clouds with NGC 2808 (Faulkner et al. 1991) and M 56 (Birkinshaw, Ho & Baud 1983) are uncertain due to their low Galactic latitudes. The paucity of observed GCG suggest that gas may be removed from the cluster on timescales as short as $< 10^6$ yr (McDonald et al. 2009). X-ray emission presumed to arise from the bow-shock interface between the GCG and the Halo gas was recently detected ahead of several globular clusters (Okada et al. 2007), suggesting that these interactions may be commonplace (cf. Faulkner & Smith 1991; Krockenberger & Grindlay 1995). This confirms the ram-pressure stripping mechanism proposed by Frank & Gisler (1976), which Priestley, Salaris & Ruffert (2008) show lead to a retention of less than a solar mass of gas.

If the gas leaving globular clusters is by and large warm neutral or weakly ionized gas, and if it retains some degree of compactness, then there might be a possibility to observe these clouds externally to clusters, perhaps ressembling compact high-velocity clouds (compact HVCs), which are found throughout the Galactic Halo (Muller et al. 1963; Wakker & van Woerden 1997; Braun & Burton 1999). With previous searches for GCG having concentrated on the cores of a small, biased sample of (generally nearby) globular clusters, a sensitive, uniform large-areal H I survey is called for to detect GCG internal or external to globular clusters.

We here report the first results of an on-going project that forms part of the Galactic Arecibo L-band Feed Array (GALFA) H I Survey presently being conducted at the Arecibo radio observatory. It has the following two objectives: (i) to search for hydrogen gas originating within Galactic globular clusters, and (ii) to search for evidence of interaction between globular clusters and the interstellar media of the Galactic Halo and Disc. We concentrate on Pal 4, in which vicinity we discovered an unusual H I cloud. As one of the most distant globular clusters known, its study may reveal properties of what is essentially *Terra Incognita* in the outer Galactic Halo. Non-detections are reported for three further clusters, viz. M 3, NGC 5466, and Pal 13, providing the most stringent limits yet on the neutral hydrogen content in these clusters.

2 ARECIBO 21 CM OBSERVATIONS

The data were collected at the Arecibo radio observatory[1], Puerto Rico, over the course of 2005–2007, as part of the Turn On GALFA Survey (TOGS). This survey runs commensally with extra-galactic drift-scan surveys as part of the Galactic Arecibo L-band Feed Array (GALFA) H I Survey (Stanimirović et al. 2006), but crossing scans from other GALFA projects have been added whenever possible to improve calibration and remove scanning artifacts. The data have a beam and channel width of $3.5'$ and 0.2 km s^{-1}, respectively; we worked with datacubes sampled at $1'$ and 0.736 km s^{-1}, respectively, covering ± 74 km s^{-1} around the velocity of the globular cluster target. Technical information about the observing strategy and basic data processing can be found in Peek & Heiles (2009).

To optimise the sensitivity of the datacube to small H I clouds, and to remove artifacts resulting from the scanning technique, we performed the following operations (in IDL): (i) apply a velocity median-filter with a running 5-channel boxcar; (ii) correct for row offsets (horizontal striping) by subtracting the median of all columns; (iii) correct for the baselines in the spectra (continuum subtraction) by subtracting the median value in the spectrum; (iv) rebin the velocity channels by a factor 4; (v) apply a spatial average-filter with a running 3×3 pixels boxcar; and finally (vi) rebin spatially by a factor 2×2. The resulting root-mean-square brightness temperature noise in the smoothed/filtered maps is $\sigma(T_{\rm B}) \sim 15$ mK.

3 GLOBULAR CLUSTER TARGETS

The targets are all globular clusters that were covered by the TOGS data as of early 2008 (Table 1). Although just four for the moment, these are interesting clusters: Pal 4 is the second-most distant cluster (after AM 1), M 3 is a rather massive cluster whilst Pal 13 is one of the dimmest clusters — believed to be near dissolution unless bound by non-luminous matter (Siegel et al. 2001; Côté et al. 2002).

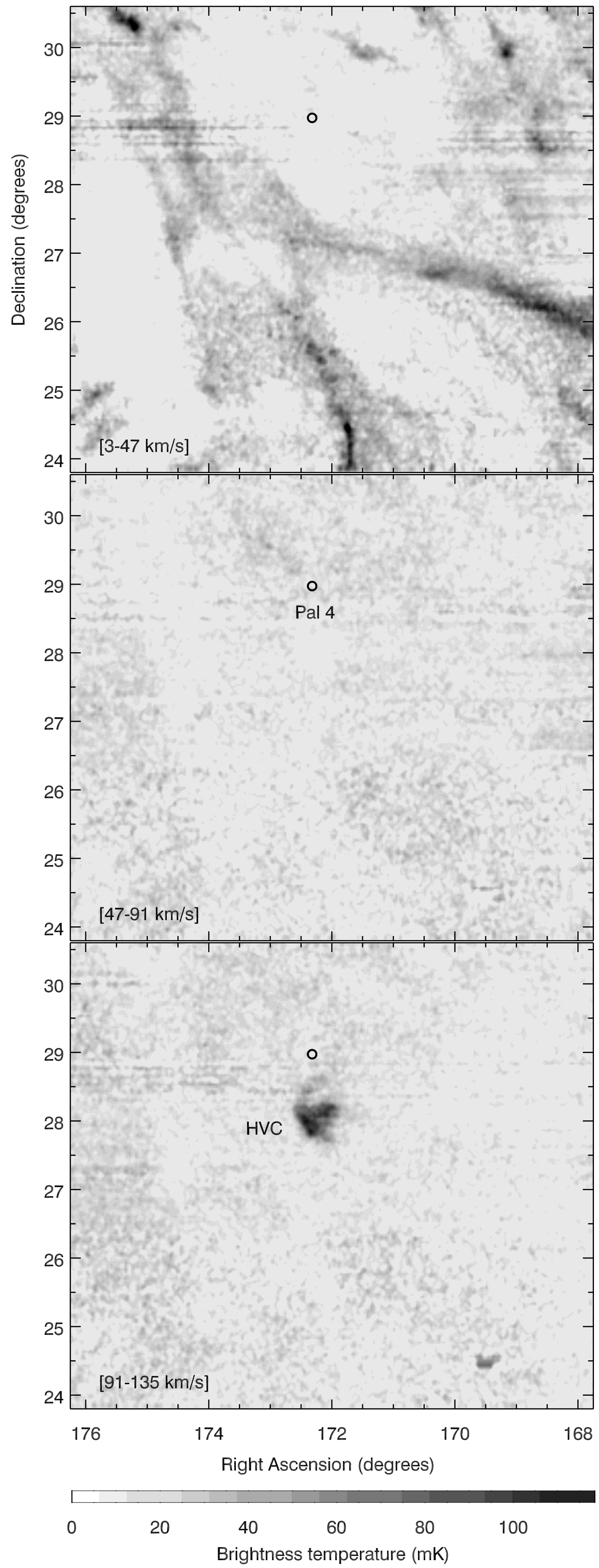

Figure 1. The 21-cm images around Pal 4 at $3'$ resolution, in velocity ranges near H I emission from Galactic cirrus (top), around the systemic velocity of Pal 4 (indicated with a circle; middle), and comprising the high-velocity cloud (HVC; bottom).

[1] The Arecibo Observatory is part of the National Astronomy and Ionosophere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation

Table 1. Globular clusters observed as part of the TOGS survey as of early 2008. Distances are given with respect to the Sun ($d_{\odot}$), Galactic Centre ($d_{\rm GC}$), and the Galactic plane (h), and $R_{\rm t}$ is the tidal radius (the half-light radii are comparable to, or smaller than, the Arecibo beam). Data are taken from the Harris (1996) catalogue, except the value for $v_{\rm LSR}$ of Pal 13 which is from Côté et al. (2002), and the cluster masses (M) which we derived from $M_{\rm V}$ employing the scaling relationship of Mandushev, Spassova & Staneva 1991). The 3-σ noise levels are given per beam and per (projected) tidal sphere ($V_{\rm t}$), in $\rm M_{\odot}$ of atomic hydrogen. These can be considered upper limits to the possible presence of GCG, and in the case of Pal 4 they do *not* include the nearby HVC.

Cluster	RA & Dec (J2000)	$v_{\rm LSR}$ (km s^{-1})	$d_{\odot}$ (kpc)	$d_{\rm GC}$ (kpc)	h (kpc)	$M_{\rm V}$ (mag)	$\log M$ ($\rm M_{\odot}$)	[Fe/H]	$R_{\rm t}$ ($'$)	H I 3-σ limit ($\rm M_{\odot}$/beam)	($\rm M_{\odot}/V_{\rm t}$)
Pal 4	11 29 16.8 +28 58 25	76.7 ± 2.1	109.2	111.8	103.7	−6.02	4.4	−1.48	3.3	30	51
M 3	13 42 11.2 +28 22 32	-137.9 ± 0.4	10.4	12.2	10.2	−8.93	5.7	−1.57	38.2	0.5	10
NGC 5466	14 05 27.3 +28 32 04	119.7 ± 0.3	17.0	17.2	16.3	−7.11	4.9	−2.22	34.2	1.6	28
Pal 13	23 06 44.4 +12 46 19	30.4 ± 0.5	26.9	27.8	−18.3	−3.51	3.2	−1.65	2.2	4.3	6

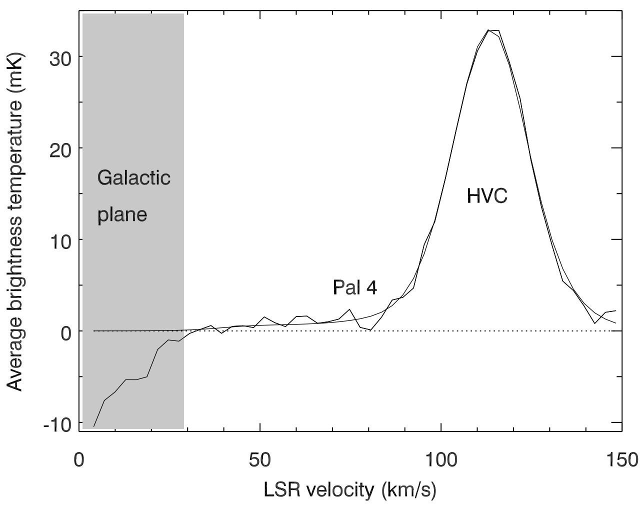

Figure 2. Line profile of the 21 cm emission in the region of Pal 4 and the nearby high-velocity cloud, averaged over a $1.15° \times 1.25°$ area. The profile dips below zero as a result of bright Galactic plane emission affecting the striping and baseline corrections.

NGC 5466 has a metallicity at the lower end of the Galactic globular clusters.

Warm GCG is expected to be in equilibrium with the gravitational potential, although a cool GCG would sink to the cluster centre (van Loon et al. 2006). One might think that M 3 presents the highest potential for detecting GCG because it may have been able to retain it within its deep gravitational potential, or alternatively Pal 4 because it may have been less perturbed and hence been able to accumulate more GCG. Both M 3 and NGC 5466 have a large projected tidal radius, possibly resulting in GCG of low surface brightness, whilst the small projected tidal radii of Pal 4 and Pal 13 could cause their GCG to under-fill the Arecibo beam thus diluting the signal. The low metallicity of NGC 5466 does not preclude the presence of H I, given that H I emission was detected from the equally metal-poor cluster M 15.

4 A PECULIAR H I CLOUD NEAR PAL 4

The Pal 4 data are intriguing: a bright cloud is found a degree to the South of the cluster (Fig. 1), offset in velocity by ~ 40 km s^{-1} (Fig. 2). The surrounding area and velocity range are otherwise rather clean, with filamentary Galactic plane emission constrained to $v_{\rm LSR} < 30$ km s^{-1} (the little smudge at $RA = 169.5°$, $Dec = 24.5°$ in the HVC panel of Fig. 1 is an artefact due to missing data). The velocity difference with respect to the maximum extension of the Galactic plane emission is > 50 km s^{-1}, classifying the cloud as a *bona fide* high-velocity cloud (HVC; Wakker 1991), and as it subtends $< 2°$ on the sky it belongs to the subclass of *compact* HVCs (Braun & Burton 1999). The weak tail of emission closer to Pal 4 has a velocity closer to that of the cluster.

This HVC is not listed in the catalogue of compact HVCs of de Heij, Braun & Burton (2002a). Birkinshaw et al. (1983) observed Pal 4 with Arecibo at 21 cm, but they did not detect the HVC as they only pointed at the cluster.

The HVC was analysed by fitting Gaussian functions to all the spectra in the datacube as processed until step (iv) described in Section 2. The fits were constrained within reason, and were successful even at a low signal level. There was no need to invoke multiple components. The fits yield maps of the peak brightness temperature, line width, and velocity centroid (Fig. 3). The line width is converted into an apparent gas temperature according to

$$\sigma_{\rm v} = (kT/m)^{0.5}, \tag{1}$$

where T is the temperature, m the mass of the hydrogen atom, and k the constant of Stefan-Boltzmann. Apart from thermal motions this temperature may include bulk motions due to turbulence or other kinematic structures.

As in Fig. 1, the circle in Fig. 3 indicates the position of Pal 4, with the circle diameter approximately equal to the tidal sphere; the HVC is located outside the gravitational dominance of Pal 4. The brightest portion of the HVC spans $\sim$half a degree in diameter, corresponding to ~ 1 kpc if at the distance of Pal 4. It has a notably bright South-Eastern rim, and otherwise displays small-scale structure down to the angular resolution limit of Arecibo — a physical scale of ~ 100 pc at the distance of Pal 4. The HVC appears fairly isothermal, and with $T_{\rm Cloud} \sim 10,000 \pm 5,000$ K typical of a warm diffuse medium. However, this is an upper limit as it includes any non-thermal contributions to the line width (e.g., turbulence). Hence, colder gas may still be present.

The H I mass of the HVC can be estimated from

$$M_{\rm H}({\rm M_{\odot}}) = 0.024\ d^2(\delta\omega/\Delta\Omega)^2 \iint T_{\rm B}(v)\,{\rm d}v\,{\rm d}A \tag{2}$$

(cf. Braun & Burton 2000), where d is the distance (in kpc), $\delta\omega$ and $\Delta\Omega$ are the pixel size and beam width, and the in-

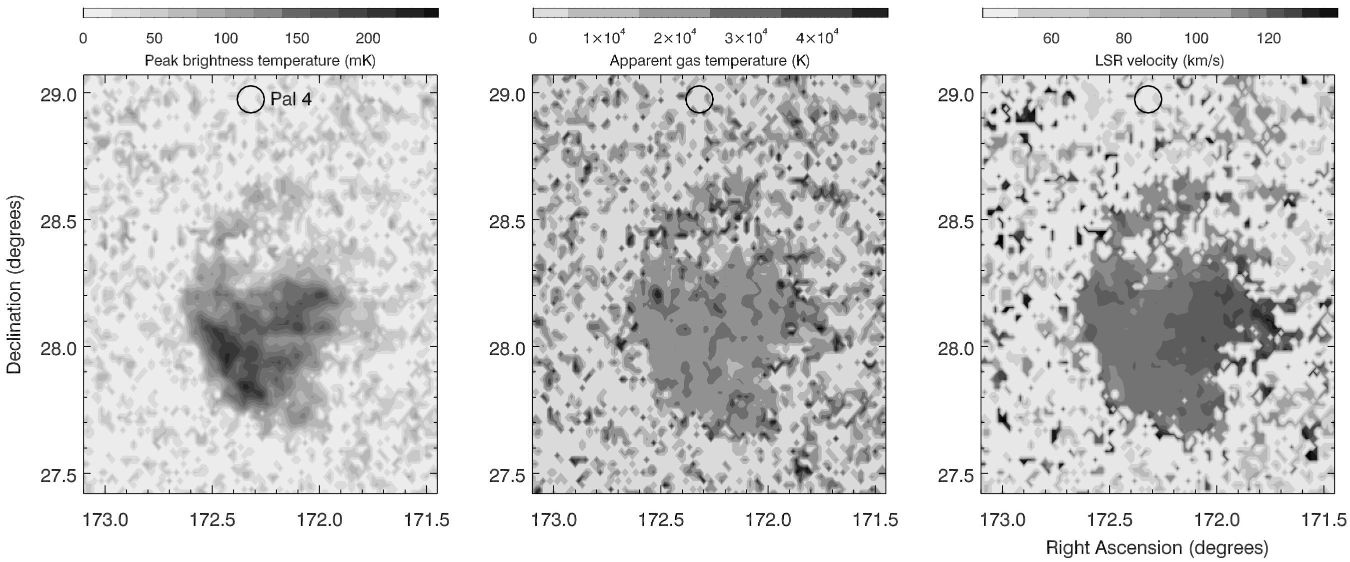

Figure 3. Peak brightness temperature (left), apparent gas temperature (middle — see text for a discussion of its meaning and caveats), and velocity centroid (right) maps constructed by Gausssian fits to the datacube.

tegration over A is simply obtained by summing the pixel values over the area covered by the H I emission, with brightness temperature $T_{\rm B}(v)$ in K and velocities v in km s^{-1}. In reality the beam is elliptical, but the resulting reduction in the mass estimate is small for a declination of $+28^\circ$ (Heiles et al. 2001). Integrating over a 44 km s^{-1} interval centred on 113 km s^{-1}, one obtains a mass of $M_{\rm H} = 8\times10^4(d/109~{\rm kpc})^2$ M$_\odot$, or $M > 10^5(d/109~{\rm kpc})^2$ M$_\odot$ if accounting for helium and perhaps additional molecular gas or hot plasma.

Although Miville-Deschênes et al. (2005) detected dust in the high-velocity Complex C, most HVCs lack dust (Peek et al. 2009) and especially the metal-poor ones have little H_2 (Richter et al. 2001). We examined the DIRBE/IRAS dust maps created by Schlegel, Finkbeiner & Davis (1998), but could not find any evidence for the presence of dust in the HVC near Pal 4. This is not surprising, especially if the HVC originates within this metal-poor globular cluster.

The HVC appears to display a velocity gradient across its surface, differing by $\Delta v \sim 10$ km s^{-1} between its Eastern and Western extremities. We dismiss the possibility that this is a result of perspective motion. In the small angle limit — which can be shown *a posteriori* to be valid — the absolute space motion of the HVC would have to be $v \approx \Delta v/\delta$, where $\delta \sim 0.6^\circ$ is the angle on the sky between the Eastern and Western extremities, i.e. ~ 1000 km s^{-1}. This would make it a *hyper*-velocity cloud, unbound to the Local Group.

If the velocity gradient were due to gravitational force, then a mass of $M_{\rm rot} = (\Delta v/2)^2 r/G \sim 3\times10^6$ $(d/109~{\rm kpc})$ M$_\odot$ is inferred, for $r \sim 0.5$ $(d/109~{\rm kpc})$ kpc. It is interesting to note that an essentially identical result is obtained if the virial theorem is applied instead, $M_{\rm vir} = (5/3)(\sigma_{\rm v})^2 r/G$, to relate the measured kinetic energy at *small* scales, $\sigma_{\rm v} \sim 10$ km s^{-1} (Fig. 3, middle), to the gravitational potential. Including the *global* kinetic structure (i.e. the velocity gradient) in this equation by replacing $\sigma_{\rm v}$ by the FWHM of the spatially-integrated line profile (Fig. 2), $\sim$ 20–25 km s^{-1}, would yield an even larger mass by a factor ~ 20; but this would be wrong as such kinetic structure is incompatible with it being a virialized (dynamically relaxed) system.

If the cloud is gravitationally confined, then the total-to-baryonic mass ratio, $M_{\rm tot}/M_{\rm bar} \lesssim 30$ $(109~{\rm kpc}/d)$, depending on the molecular and ionized content (Pal 4 itself is outside the dynamical region considered here). If all baryonic mass were atomic then $M_{\rm bar} \sim M_{\rm H+He}$. For the atomic mass detected via H I to account for all of the dynamical mass ($M_{\rm tot}$), the distance would have to be $d \sim 3$ Mpc. At such large distance the cloud would be ~ 30 kpc in diameter, i.e. the size of a typical spiral galaxy. If the velocity gradient is indeed due to rotation under the influence of gravity, then this ratio *increases* if the cloud is nearer to us.

But velocity gradients of this size are often seen in HVCs (e.g., Westmeier, Brüns & Kerp 2005). The dynamical mass estimate may therefore not be valid and the cloud mass may be similar to the estimate based purely on H I. In some cases velocity gradients result from a superposition of several H I clouds (e.g., Stanimirović et al. 2002). Yet the HVC near Pal 4 is not part of an extensive complex of H I clouds such as make up the Magellanic Stream, so one then wonders about the cause for — and sustainability of — the kinematic substructure within this isolated cloud.

5 UPPER LIMITS ON NEUTRAL HYDROGEN WITHIN M 3, NGC 5466, PAL 4 AND PAL 13

No gas is found within any of the globular clusters, M 3, NGC 5466, Pal 4 or Pal 13. We have estimated 3-σ noise levels, expressed in M$_\odot$ of atomic hydrogen mass contained within an Arecibo beam as well as within the projected tidal sphere of the cluster, valid for H I emission originating at the cluster distance (Table 1).

The M 3 and NGC 5466 data show no H I emission at all (Fig. 4). These clusters have tidal radii in excess of half a degree, which results in relatively high upper limits to the hydrogen mass if spread out over the tidal sphere. A tidal tail was discovered associated with NGC 5466 (Belokurov et

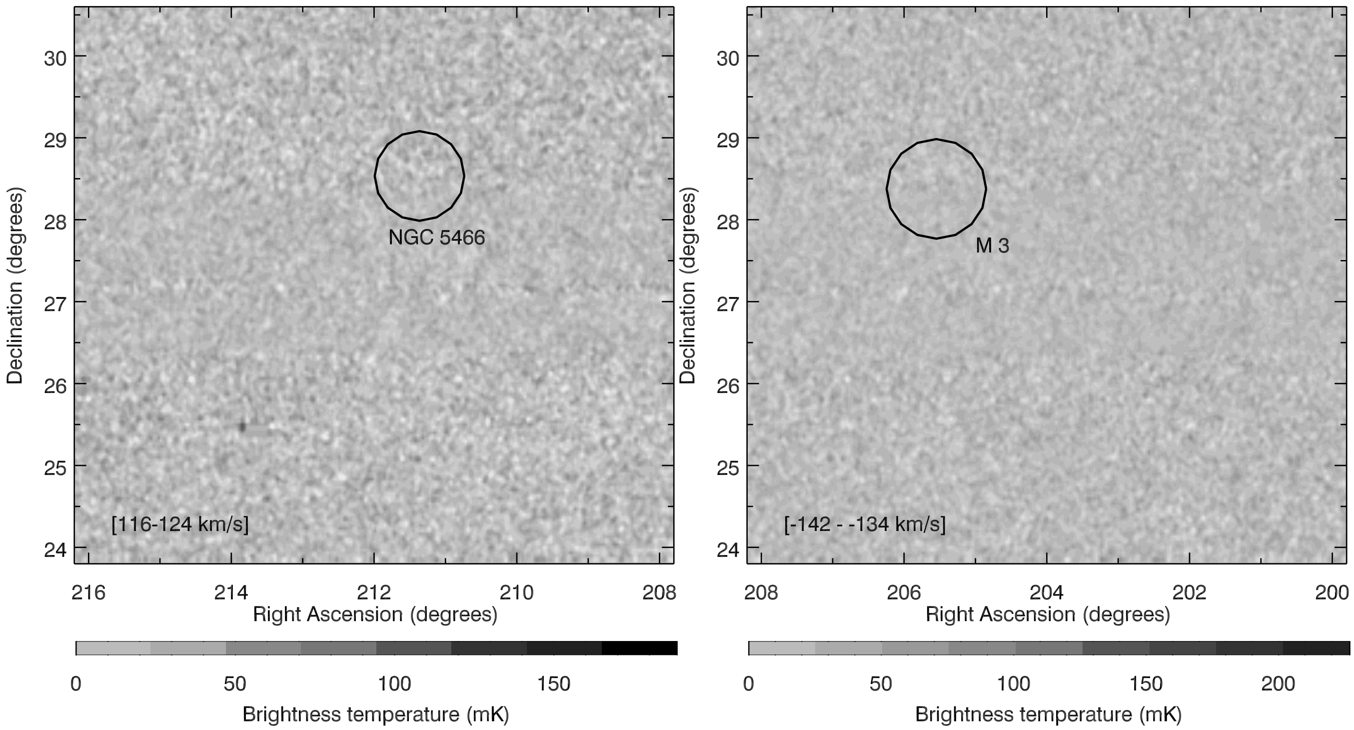

Figure 4. The 21-cm images around NGC 5466 (left) and M 3 (right), in a 9 km s^{-1} velocity range around the H I emission at each of their systemic velocities. The size of the circle represents the extent of the tidal sphere in each case.

al. 2006), and the gas may have been susceptible to tidal stripping as well. The stellar tidal tail runs diagonally from SE to NW over $\sim 4°$, between about ($RA = 214°$, $Dec = 27°$) and ($RA = 210°$, $Dec = 30°$) (Belokurov et al. 2006). No H I emission was detected either within our outside this. Although we could search even larger areas, it would be hard to establish a link between cluster and gas for separations more than a few degrees.

The Pal 13 data are confused with Galactic Disc emission. Although some emission is concentrated near the cluster in position and velocity, at slightly smaller velocities this emission is clearly part of an extended interstellar cirrus complex (Fig. 5), which is around $l = 87°$, $b = -43°$. This cluster is one of the least massive globular clusters known, and is unlikely to have accumulated much GCG.

M 3 and NGC 5466 were observed at Arecibo before, by Birkinshaw et al. (1983) who derived upper limits of 45 M$_\odot$ within the tidal sphere and 0.61 M$_\odot$ per beam for M 3, and 1190 and 1.7 M$_\odot$, respectively, for NGC 5466. The new scanning observations place more stringent limits on the mass contained within the large tidal radii. Birkinshaw et al. also observed Pal 4, but they searched a velocity range $v_{\rm LSR} > 105$ km s^{-1} which excludes that of Pal 4. Thus, ours is the first meaningful upper limit on H I emission from Pal 4. We observed Pal 13 at Arecibo before (van Loon et al. 2006), failing to detect anything more significant than a 3-σ level of 1 M$_\odot$ (we did detect the Northern tip of the Magellanic Stream, behind the cluster). Our new upper limits for Pal 13 are higher, but more realistic given the complex contamination from interstellar cirrus.

6 DISCUSSION: H I IN REMOTE CLUSTERS

No H I emission could be detected in the massive cluster M 3, and searches for H I emission from other massive clusters have been equally unsuccessful (save for M 15). A typical globular cluster produces $\sim 10^{2-3}$ M$_\odot$ of gas between successive cleansings when passing through the Galactic plane (Tayler & Wood 1975; McDonald et al. 2009). There is evidence for clusters to be stripped of their gas on much shorter timescales, possibly through interaction with the Galactic Halo (van Loon et al. 2006; Boyer et al. 2006). Our non-detection in M 3 once again confirms the rapid removal timescale. Pal 4 on the other hand is not very massive: $M \sim 2-3\times10^4$ M$_\odot$, from the relation with $M_{\rm V}$ (Mandushev et al. 1991). Our measurements allow ~ 40 M$_\odot$ of atomic hydrogen to be present within the tidal volume of Pal 4, i.e. of similar order to what is expected to have accumulated over a Gyr.

Perhaps the presumptions about the most likely hosts of significant amounts of GCG have been wrong. The nearer clusters experience much higher degrees of harrassment by the Galactic Halo and Disc than very distant clusters. Even the high metallicity of some prime targets may have fooled us in the past, if the winds of metal-poor stars are slower (Marshall et al. 2004) and hence more likely to be retained within the cluster's gravitational potential (cf. McDonald & van Loon 2007) — explaining the detection in one of the most metal-poor clusters, M 15 (van Loon et al. 2006).

Below, we discuss the prospects of finding gas associated with distant globular clusters, and in particular the likelihood of association of Pal 4 with the HVC next to it.

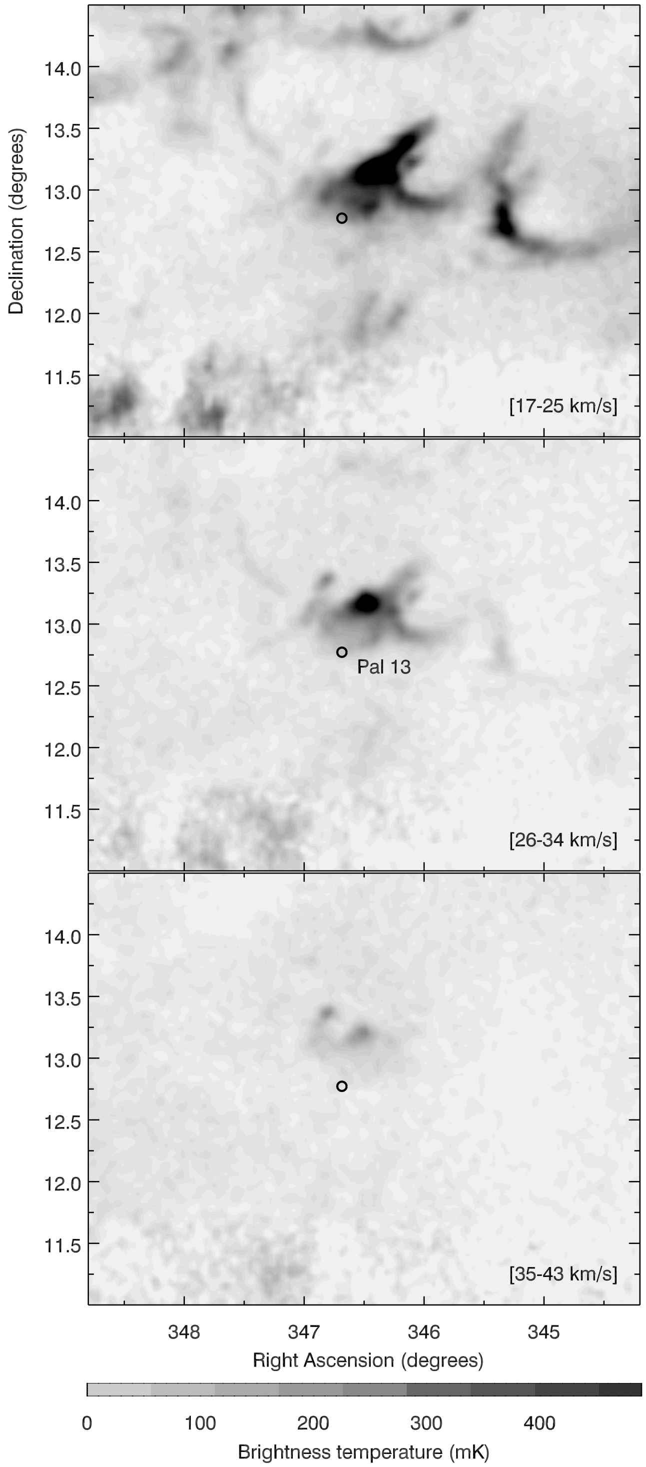

Figure 5. The 21-cm images around Pal 13, in velocity ranges near H I emission at the systemic velocity of Pal 13 (indicated with a circle; middle), and slightly shifted in velocity (top/bottom).

6.1 Constraints on the distance to the HVC and the likelihood of its association with Pal 4

HVCs were found within ~ 50 kpc from M 31 (Westmeier, Brüns & Kerp 2008), and where distances have been derived to Galactic HVCs they tend to be ~ 10 kpc (Putman et al. 2003; Thom et al. 2006, 2008; Wakker et al. 2007, 2008). Either the HVC we discuss here is associated with Pal 4 (which would explain that it is not as nearby as other HVCs) or it is much closer to us like other typical HVCs (and thus not associated with Pal 4). Can we distinguish between these two possibilities?

Pal 4 is seen in a direction away from the Galactic Centre and Galactic plane ($l = 202^\circ$ and $b = +72^\circ$). An extended complex of extra-planar gas is seen in that general direction of the sky, e.g., in the Leiden-Argentine-Bonn survey (Kalberla et al. 2005). The HVC near Pal 4 is marginally consistent with the "population P" proposed by Wakker & van Woerden (1991), which they note tend to be small clouds and with velocities suggesting they may belong to the outer realms of the Galaxy. De Heij et al. (2002a) also found several HVCs and compact HVCs with $90 \lesssim v_{\rm LSR} \lesssim 130$ km s^{-1} at distances of $\geq 5^\circ$ from Pal 4, which they argue are consistent with a population of dark-matter halos in the Local Group (de Heij, Braun & Burton 2002b).

As noted in the previous section, the HVC near Pal 4 must be moving away from the Milky Way at high speed. This is unlikely for the majority of the HVCs, which Braun & Burton (1999) point out may be the reason for the paucity of HVCs observed in the direction of the Galactic poles. As Pal 4 is also moving away from the Milky Way a link is plausible. The orbital velocity of Pal 4 is not known but likely to be of order 200 km s^{-1}, and it must therefore have a significant (but hard to measure) transversal velocity. If this is true also for the HVC, then one could expect significant deformation due to the interaction (through ram-pressure) with the Halo gas even at the relatively low densities at the distance of Pal 4. Indeed, the HVC resembles the head-tail morphology seen in many HVCs and explained in this way (Westmeier et al. 2005). From this, we would predict a motion of the HVC in a South-Eastern direction.

6.1.1 *Constraints from cloud dynamics and morphology*

Pressure equilibrium: The atomic density in the HVC, for a volume of ~ 0.1 $(d/109$ kpc$)^3$ kpc^3, is $n_{\rm Cloud} \sim 3 \times 10^{-2}$ (109 kpc$/d$) cm^{-3}. For it to be in pressure equilibrium with the surrounding Halo gas, the Halo density must be $n_{\rm Halo} = n_{\rm Cloud} \times (T_{\rm Cloud}/T_{\rm Halo}) \sim 3 \times 10^{-4}$ (109 kpc$/d$) cm^{-3}. This is ~ 5 times higher than other estimates of the Halo density (Bregman 2007; cf. Sembach et al. 2003). The density profile of the Halo falls approximately as $1/d$ (see Sternberg, McKee & Wolfire 2002), so placing the HVC nearer or farther away will not improve the agreement.

Gravitation helps to keep the cloud together. Following Westmeier et al. (2005) we computed the external pressure required to keep the HVC bound in addition to gravitation by the cloud mass, assuming the virial theorem holds (and setting $\sigma_{\rm v} \equiv 10$ km s^{-1}). This depends on the distance and on the fraction, f, of H I plus helium mass compared to the total mass (Fig. 6). For $\log f \gtrsim -1.5$ we obtained reasonable values for the Halo pressure for distances as short as 10 kpc and as long as several 100 kpc (see Sternberg et al. 2002, their figure 14).

Thermal and dynamical instabilities: One may expect thermal instabilities to occur due to cooling, as well as Kelvin-Helmholtz instabilities due to friction with the hot Halo. The thermal spatial and temporal scales scale with

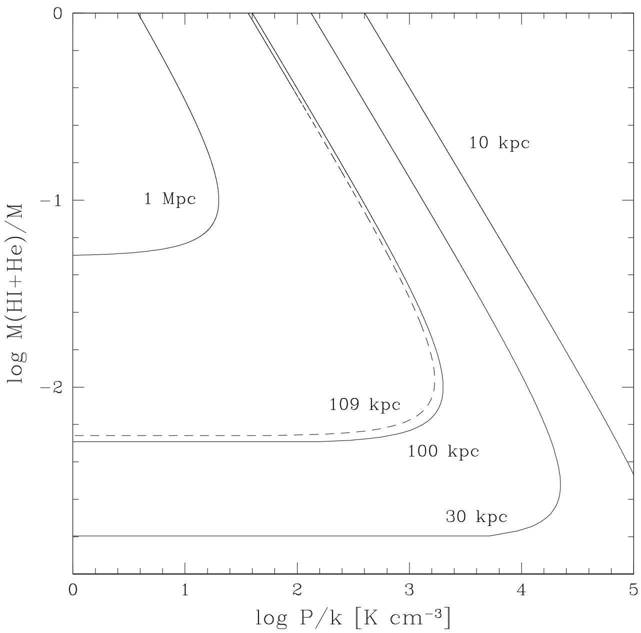

Figure 6. Diagram computed for the HVC near Pal 4, of the external pressure, P, required to keep the cloud stable, for different fractions of H I plus helium mass compared to the total mass, and for different distances. Pal 4 is at 109 kpc (dashed curve). This assumes the virial theorem holds, and that $\sigma_{\rm v} = 10$ km s^{-1}.

$n_{\rm Cloud}^{-1}$, whilst the Kelvin-Helmholtz timescale scales with the square root of the cloud–halo contrast (cf. Stanimirović et al. 2008). Both are $\sim 10^8$ yr for $\sim$ kpc fragments, for the density derived at $d = 109$ kpc and a (distance independent) cloud–halo density contrast ~ 100. This could explain why the cloud is confined to ~ 1 kpc size, and the timescale is similar to the plausible duration for the cloud to have been separated from Pal 4.

Fluctuations in brightness temperature are seen across the surface of the HVC on smaller scales, about 6–20′. If these are the relevant scales at which thermal instabilities are operating in the HVC, they would correspond to physical sizes $\sim$ 200–600 (d/109 kpc) pc. In fact, Stanimirović et al. (2008) estimate scales of $\sim$ 100–200 (5×10^{-2} cm$^{-3}/n$) pc. These two estimates can be reconciled with the above estimated density of the HVC, suggesting thermal instabilities on scales of 200–300 (d/109 kpc) pc. Interestingly, this does not depend on distance, but it does require that the majority of the gas is accounted for by the warm neutral medium traced by H I.

Differential drag: The arc-like feature ("tail") to the North of the bulk of the HVC emission, at the side of Pal 4, might be interpreted as the result of differential drag as the cloud moves through the Halo. Peek et al. (2007) presented a simple prescription of what might be expected:

$$n_{\rm H}\ d = \frac{1}{C_{\rm D}} \left(\frac{\Delta v}{v}\right)^2 \frac{\sin\phi}{\Theta \Delta N_{\rm H}^{-1}}, \tag{3}$$

where $C_{\rm D}$ is a drag coefficient, ϕ is the angle between the cloud's motion and the line-of-sight, and Θ is the angular separation between the HVC and its tail.

We estimate that the relative velocity difference is $\Delta v/v \simeq 10/100$, $\Theta \simeq 0.5^\circ$, and the neutral hydrogen column densities $N_{\rm H} \sim 3 \times 10^{18}$ and $\sim 10^{19}$ cm^{-2} in the tail and main body, respectively. Assuming $\sin\phi \sim 0.5$ and $C_{\rm D} \simeq 1$ (see Peek et al. 2007), we thus obtain $n_{\rm H}\ d \sim 3 \times 10^{18}$ cm^{-2} or $n_{\rm H} \sim 1 \times 10^{-5}$ (109 kpc/d) cm^{-3}. This is low, but given the uncertainties it is still consistent with measured Halo gas densities. For instance, $C_{\rm D}$ might be a few times smaller and hence the derived density a few times higher. The $1/d$ dependence of $n_{\rm H}$ renders $n_{\rm H}\ d$ distance independent.

Multiphase medium: Clouds near the Galactic plane can (but do not always) exhibit multi-phase structure (Wolfire et al. 1995). Recent studies suggest a multi-phase medium may exist even at distances as large as 150 kpc (Sternberg et al. 2002). The HVC near Pal 4 seems uniformly warm, but the presence of a cold phase can not be excluded. The apparent warmth could be entirely due to non-thermal motions (e.g., turbulence), although it would be coincidental if it led to the observed temperature of 10,000 K so common for warm interstellar gas. The presence of a warm neutral medium seems therefore likely, but if this is the case then it could easily mask a modest amount of cold medium. Either way, this lends us no clues with regard to its distance.

Relatively nearby clouds tend to shine in Hα due to heating by the Galactic Disc (radiatively) or Halo (kinetically) (Bland-Hawthorn et al. 1998; Tufte et al. 2002; Putman et al. 2003). In the Magellanic Stream, shock cascades running downstream cause it to light up in Hα (Bland-Hawthorn et al. 2007). One would not expect an isolated cloud at 109 kpc to be bright in Hα, the meta-Galactic radiation field being too weak. The expected brightness of the HVC is $S = n^2 L$ mR, where the density, n, is in cm^{-3} and the extend along the line-of-sight, L, is in kpc. Assuming a spherical cloud, we obtain $S = 10$ (109 kpc/d) mR. This is faint, but a little above the detection limit of the most sensitive all-sky Hα survey, viz. the Wisconsin Hα Mapper (WHAM; Haffner et al. 2003). Unfortunately, the velocity coverage of WHAM was too restrictive, only barely reaching the velocity of Pal 4.

6.1.2 Constraints from sodium absorption

The presence or absence of absorption signatures of the cloud in the spectra of background objects at known distances can help constrain the distance to the cloud (e.g., Thom et al. 2006, 2008; Wakker et al. 2008). For this experiment we considered Sloan Digital Sky Survey Data Release 7 (SDSS-DR7; Abazajian et al. 2009) spectra of the strong Na I D doublet around 589 nm that is commonly seen in the neutral and weakly-ionized medium.

The spectral resolution is ~ 30 km s^{-1}; this is about three times the expected intrinsic line width judged from the observed velocity dispersion of the HVC on arcminute scales, but the intrinsic line width will be narrower still if $\sigma_{\rm v}$ drops at sub-arcminute scales and/or if $\sigma_{\rm v}$ is dominated by thermal motions in which case the heavier sodium atoms display smaller velocities than the hydrogen atoms.

We first compiled a composite of 16 stars of spectral types A–G, with velocities between $-30 \le v_{\rm LSR} \le 30$ km s^{-1}, to show a typical Na I D doublet (Fig. 7). In this case, the absorption arises mostly or entirely in the photosphere of the stars; to test our ability to discern redshifted absorption, we also compiled a composite of similar stars with velocities between $90 \le v_{\rm LSR} \le 180$ km s^{-1} and indeed the photospheric absorption is redshifted by a detectable amount.

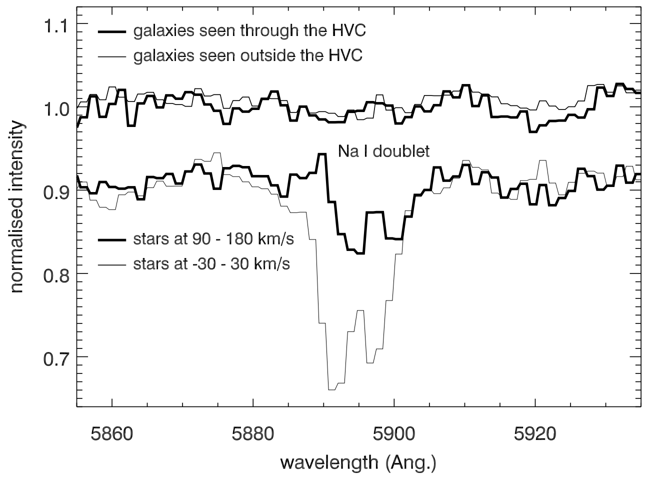

Figure 7. Sloan Digital Sky Survey (SDSS) spectra around the Na I D doublet, of the averages of galaxies seen through the HVC and near to it, and of example averages of stars (offset by −0.1 for clarity) with velocities around zero and around that of the HVC to illustrate the ability to detect the redshift of the HVC. The line absorption in the stellar spectra arises in the stellar photospheres; the galaxy spectra (a mixture of redshifts) show very little interstellar absorption.

We then retrieved the spectra of 298 *galaxies*, that are definitely behind the HVC, to check whether any intervening absorption could be detected at all. We only selected galaxies with redshifts that avoided direct blends with strong spectral lines in the intrinsic galaxy spectrum. Otherwise, the redshifts vary and the expectation was that this would lead to annihilation of the features in the galaxy composite whilst maintaining any intervening absorption which does not partake in the galaxy's redshift. This worked very well (Fig. 7): the galaxy composite shows a featureless continuum to within approximately ±2%.

Comparing galaxies seen through the HVC (within 0.3° from its centre) and those surrounding it, we see that the difference is very small and one cannot say with any certainty whether there is absorption redshifted by the amount expected for the HVC. It is clear that the experiment using Halo stars would not give any useful result. We thus place an upper limit to the Na I D absorption of $W \lesssim 0.1$ Å or $N_{\rm NaI} \lesssim 10^{12}$ cm^{-2}.

For scaled-solar abundances $N_{\rm Na} \sim 2\times10^{-5}\ N_{\rm H}\ (Z/{\rm Z}_\odot)$ (Grevesse & Noels 1993). With $N_{\rm H} \sim 10^{18-19}$ cm^{-2} in the HVC near Pal 4 this would imply $Z_{\rm HVC} < 0.1\ {\rm Z}_\odot$. HVCs in the inner Halo generally have metallicities 0.1–1 Z$_\odot$ (Richter et al. 2009, and references therein), but Pal 4 has a metallicity $Z_{\rm Pal\,4} = 0.03\ {\rm Z}_\odot$. The non-detection of Na I in the HVC is thus more consistent with an origin in Pal 4 than with typical HVCs closer to the Milky Way. But the uncertainties are substantial and the upper limit on the sodium column density is not inconsistent with typical values found in extra-planar gas (Ben Bekhti et al. 2008).

6.1.3 *Summary on constraint on the HVC distance*

We have considered several possibilities to constrain the HVC distance. The assumption of pressure equilibrium, the spatial and temporal scales at which instabilities occur, the likelihood of a multi-phase medium, and limits on the metal content all point at a distance $10 \lesssim d \lesssim 200$ kpc. This does not discriminate between an association of the HVC with Pal 4 and a chance alignment of the two.

6.2 Distant globular clusters as probes of the outer Galactic Halo

The most distance cluster in our sample, Pal 4 is the only one with a possible gas association. Distant globular clusters might well be the most likely places to find large amounts of GCG, because they have not passed through the Galactic Disc for some time, and the Galactic Halo is relatively tenuous that far from the Galactic Centre. The same is true for other satellites of the Milky Way, such as low-mass dwarf galaxies some of which have been found at distances comparable to the Magellanic Clouds (e.g., Willman et al. 2005).

Pal 4, like the other distant clusters Pal 3, Eridanus, Pal 14, and AM 1, appears to be 1.5–2 Gyr younger than the inner Halo globular clusters (Forbes, Strader & Brodie 2004; Dotter, Sarajedini & Yang 2008). Red giants in these clusters would lose more mass than their older, lower-mass siblings, thus enhancing the rate of GCG replenishment. This could alleviate the problem of the large inferred mass for the HVC, but only slightly.

Also, Pal 4 presently traverses the far outskirts of the Galactic Halo; it will definitely have had much longer than usual to accumulate the slow ejecta from its red giants. In fact, its trajectory is undetermined, and it may not even be in orbit around the Milky Way, and never have passed through the Galactic Disc.

In addition, the HVC may have collected much of its mass from Halo gas swept up by Pal 4: e.g., for a column of 0.2 kpc diameter (Pal 4's tidal cross-section) and 1.3 Mpc length (two circular orbits), it would have swept up a similar amount of matter as is currently observed. This requires that the gas is collected through ram-pressure interaction with gas already filling the tidal sphere; accretion by gravity would not work as the speed of Pal 4 relative to the Halo gas exceeds the cluster's escape velocity by an order of magnitude and gas entering an "empty" Pal 4 would just as easily leave it again through the backdoor.

The displacement of $\sim$ 2 kpc between the HVC and Pal 4 (if at a common distance) corresponds to a timescale of 5×10^7 yr, assuming a relative velocity of 40 km s^{-1}. This becomes longer if they differ in distance to us and their relative motion across the sky is slower than along the line-of-sight — or potentially shorter if the relative motion across the sky is faster. In fact, much of the observed radial velocity component is away from the Galactic Centre, meaning that the HVC is moving away from the Milky Way at considerable speed, $\sim$ 90 km s^{-1} (if it is at $d \gtrsim 100$ kpc), and faster than Pal 4 does ($\sim$ 50 km s^{-1}). This implies that if the HVC was once part of Pal 4, that it must have been accelerated during or since it had become detached from the cluster.

We speculate that possible acceleration mechanisms might include large-scale convection (from a combination of buoyant hot gas cells and cooling flows) within the Halo, or a coronal (pressure-driven) or disc (radiation-driven) Galactic wind (cf. Veilleux, Cecil & Bland-Hawthorn 2005). Either of these scenarios would imply an external pressure (by gas or radiation) being the source of acceleration, rather than

an internal source (as in a rocket). The observed head-tail morphology of the HVC would arise naturally: assuming the HVC is in the background of Pal 4, then its "head" points roughly at the Milky Way (and Pal 4).

GCG removal timescales of the order of 10^6 yr have been inferred for clusters much deeper in the Galactic Halo, typically $\sim$ 10 kpc from the Milky Way (van Loon et al. 2006; Boyer et al. 2006; McDonald et al. 2009). At the distance of Pal 4, the Halo density is two orders of magnitude lower (Sternberg et al. 2002); stripping is thus much less effective. It will take gas in Pal 4 two orders of magnitude longer to have run into the equivalent amount of Halo material as nearby globular clusters, i.e. 10^8 yr. This compares well with the above estimate of the dynamical timescale if the HVC has been removed from Pal 4.

If the Halo gas is effective in removing GCG from globular clusters, then the more likely place to catch it is not inside the cluster but at some distance trailing it. This might explain the small offset from the cluster centre of the cloud discovered in M 15 (Boyer et al. 2006), as well as the cloud we now discovered near Pal 4. This would be slightly at odds with the interpretation of X-ray emission *in front* of several clusters to be due to bow-shock interaction between the GCG and the Halo gas (Okada et al. 2007). Perhaps, whether a bow-shock or trailing cloud is observed depends on the pressure balance between the GCG and Halo.

6.2.1 *Could we have discovered a dark galaxy?*

Dark mini-halos are predicted by ΛCDM cosmologies to swarm the Local Group (Kauffmann, White & Guiderdoni 1993). Some of these may never have ignited to become one of the luminous dwarf galaxies that are being discovered in increasing numbers (cf. Simon & Geha 2007). Completely dark halos would obviously be hard to find. Does the large mass for the HVC near Pal 4 as inferred from its apparent rotation bear evidence of a dark galaxy host to the HVC and Pal 4? If the relative velocity of Pal 4 also reflects an orbital motion around the cloud, then the enclosed mass may be as high as 10^8 $M_\odot$ (or higher depending on the orientation of the orbit), i.e. at least several hundred times the combined masses seen in the HVC's H I and Pal 4's starlight. If this is the case, one must consider this system a dark halo.

The object may not be strictly dark. To search for a stellar counterpart to the HVC, we have mined the Sloan Digital Sky Survey Data Release 6 (SDSS-DR6). Based on the location in the $(g-r), r$ colour-magnitude diagram of stars within $1.8'$ from Pal 4, we defined a locus of relatively numerous red giants and horizontal branch stars (Fig. 8, top). Plotting stars that satisfied this photometric criterion within a 1° radius from (RA,Dec)=(172°,28.1°) revealed no obvious overdensity apart from Pal 4 (Fig. 8, bottom). Some clustering may be present near (RA,Dec)=(171.8°,27.6°), but this is hardly convincing and in any case would not amount to more than the equivalent of Pal 4.

The faint dwarfs that have recently been discovered near the Milky Way have typically a radius of $\lesssim 10'$, and a surface brightness $\mu_{\rm V} \sim 29$ mag arcsec^{-2} but perhaps as dim as 31 mag arcsec^{-2} (Liu et al. 2008). If the light of Pal 4 were to be spread out over a square degree, it would have $\mu_{\rm V} \sim 32.7$ mag arcsec^{-2}. A low-luminosity system such as Willman 1 (Willman et al. 2005) — which incidentally has a metallicity

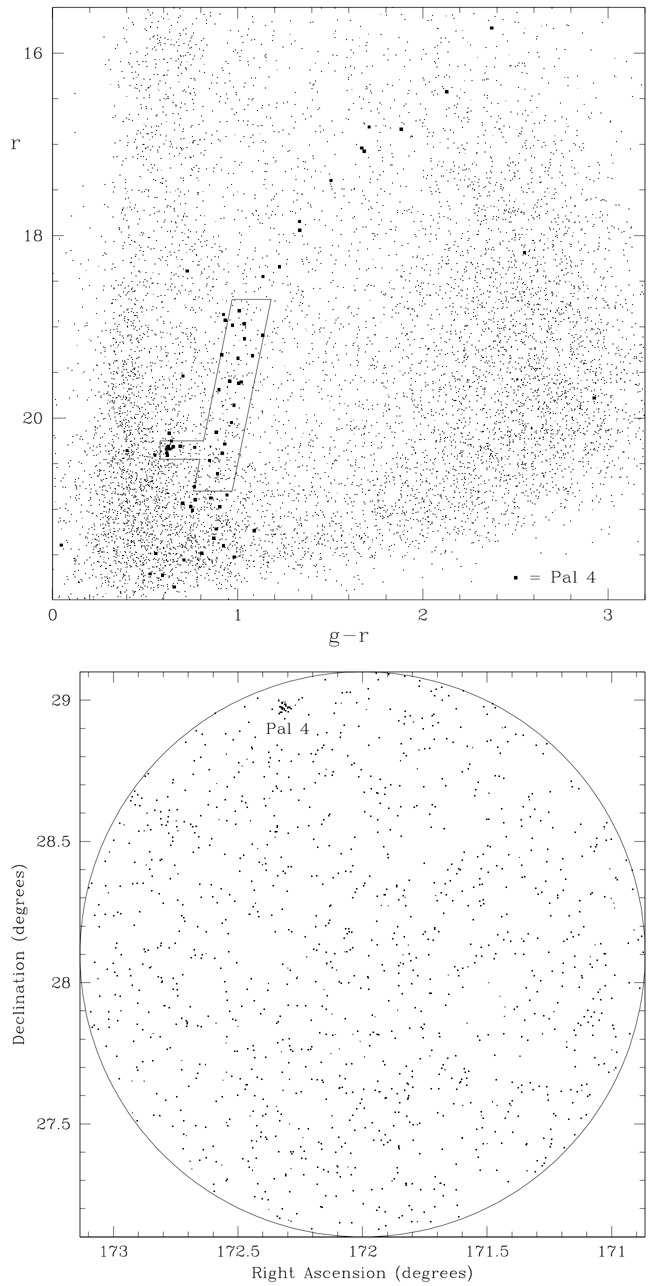

Figure 8. Sloan Digital Sky Survey (SDSS) photometry in Pal 4, and within a 1° radius field centred on (RA,Dec)=(172°,28.1°) (top panel). The positions on the sky of stars within the box are plotted in the lower panel, comfortably encompassing the HVC.

similar to that of Pal 4 (Siegel, Shetrone & Irwin 2008) — would have been very hard to detect indeed if it were as diffuse as the HVC. It seems thus likely that, if the HVC near Pal 4 contains $> 10^6$ $M_\odot$, it must be pretty dark.

7 CONCLUSIONS

Using GALFA-H I Survey data, we searched for neutral hydrogen gas associated with four Galactic globular clusters, M 3, NGC 5466, Pal 4, and Pal 13. No gas was found within the tidal radii of any of these clusters, down to 3-σ limits

of 6–51 $M_\odot$. These represent the most stringent limits on the gas content of these clusters to date. In the case of the massive cluster M 3 this confirms once again that efficient removal mechanisms must be at work that clean globular clusters of gas on timescales of $\ll 10^8$ yr.

We did discover a compact H I high-velocity cloud (HVC) near Pal 4, which at 109 kpc distance from the Sun is one of the most remote clusters in the Galactic Halo. The properties of the cloud resemble those of other HVCs located nearer to the Milky Way, but its high velocity directed away from the Galaxy and its relative isolation but proximity to Pal 4 are tantalizing — a physical association between the two remains possible. However, one would need to invoke rather extreme descriptions for the interaction of the Pal 4/HVC system with the Milky Way halo, to account for the following observations:

- The HVC lies beyond the gravitational influence of Pal 4;
- The H I mass of the HVC exceeds that of Pal 4;
- Their galacto-centric velocities differ by 40 km s^{-1}.

The internal kinematics of the cloud suggests an even higher mass, 3×10^6 $M_\odot$ if at the distance of Pal 4. Most of this mass must be either cold ($\lesssim$100 K), very hot ($\gtrsim 10^6$ K), or dark (non-baryonic). If it is cold it might be possible to detect in a high angular resolution H I absorption-line experiment. If it is very hot it might be detectable in X-rays — although there is no *a priori* reason to expect such hot plasma. On the other hand, if the H I structure seen in the HVC on 0.1–1° scales is due to thermal instabilities then most of the gas is likely to be traced by H I. But this does not preclude the cloud and Pal 4 being the flimsy tracers of a dark mini-halo, a relic of the re-ionization epoch in which star formation might only have led to the production of Pal 4[2]. This may fit a scenario proposed recently by Ricotti (2009) for the late gas accretion by primordial mini-halos to explain faint dwarf galaxies like Leo T and some HVCs. In this scenario, Pal 4 would orbit the dark mini-halo, the inferred mass of which would then be quite phenomenal ($\gtrsim 10^8$ $M_\odot$). This "mini"-halo would indeed be largely dark, having accreted only the gas we see in the form of the HVC.

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[2] We would like to point out that Pal 4 is in the constellation of Ursa Major, but the H I column density of the HVC has its maximum just across the border, in the constellation of Leo.

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